9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Improving high-temperature capacitive energy storage of biaxially oriented polypropylene using atmospheric pressure plasma jet

Chuansheng Zhang[1, 2], Li Lv[1], Fan Li[1, 2], Chengyan Ren[1,2], Tao Shao[1, 2]
[1] Beijing International S&T Cooperation Base for Plasma Science and Energy Conversion, Institute of Electrical Engineering, Chinese Academy of Sciences
[2] University of Chinese Academy of Sciences
e-mail (speaker): zhangchs@mail.iee.ac.cn

Biaxially oriented polypropylene (BOPP) films have become the dielectric material of choice for film capacitors due to their superior energy storage capabilities. However, their practical application in high-temperature environments faces a critical challenge: significant deterioration of energy density. This instability necessitates the development of effective surface modification strategies to enhance their high-temperature performance. To meet industrial production requirements, ideal modification approaches should satisfy four key criteria: 1) high processing efficiency for continuous manufacturing, 2) cost-effectiveness in both materials and implementation, 3) environmental compatibility with minimal hazardous byproducts, and 4) utilization of readily available raw materials to ensure supply chain stability. Current research focuses on atmospheric pressure plasma treatment techniques that demonstrate potential in achieving these industrial objectives [1].

Atmospheric pressure plasma jet (APPJ) demonstrates superior operational flexibility and excitation efficiency [2, 3], capable of generating plasma plumes. However, atmospheric pressure plasma treatment in ambient air tends to generate filamentary discharges when directly interacting with substrate materials, which can induce surface defects and deterioration of insulation properties. This limitation therefore requires the implementation of argon gas with low ionization potential as the working medium to ensure stable discharge characteristics. The plume length and relative positioning can be adjusted according to the material's thermal sensitivity without triggering discharge mode transition. For BOPP film modification applications, the treatment system employs a high-frequency high-voltage AC power supply (5-6 kV output, 37.6 kHz frequency) to energize the plasma jet. The nozzle-to-film distance is typically maintained at 10 mm, with the treatment temperature controlled at only 10-30°C above ambient conditions. This configuration ensures effective surface modification while preserving the structural integrity of the polymer matrix.

APPJ enables rapid deposition of wide bandgap nanostructured functional coatings, achieving surface modification within an ultra-short 30-second processing window. This nanoscale coating technique ensures homogeneous surface engineering while providing long-term performance stability. Taking TiO_2 layer deposition as a representative case, the plasma treatment temperature remains significantly below the anatase-to-rutile phase transition temperature (typically 600-800°C), resulting in predominant anatase-phase TiO_2 formation on BOPP films. The deposited functional layer demonstrates a significantly enhanced relative permittivity of $\varepsilon \approx 48$, yielding a 21.8-fold increase compared to the intrinsic dielectric constant of pristine BOPP ($\varepsilon \approx 2.2$). This remarkable dielectric enhancement directly contributes to the improved energy storage capacity observed in the modified composite, and achieves a 31.3% enhancement in discharge energy density (120°C: 3.2→4.2 J/cm³) with η~90%.

This work is supported by the National Natural Science Foundation of China-State Grid Joint Fund for Smart Grid (Grant No. U2166215) and National Natural Science Foundation of China (Grant No. 52477166).

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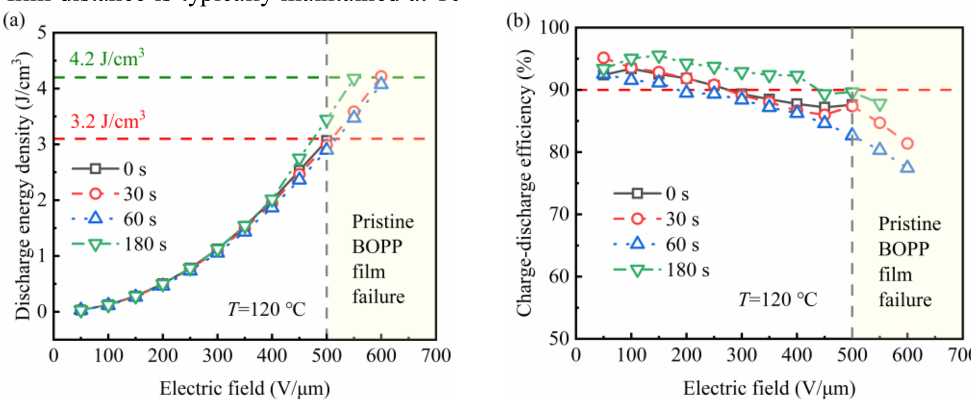

Figure 1. Energy storage performance enhancement in plasma-treated BOPP/TiO_2 composite films: (a) 31.3% energy density boost to 4.2 J/cm³ at 120°C, (b) Sustained 90% charge-discharge efficiency under high field conditions.